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Title: BEAMPATH User Manual

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Intended for: Program Distribution
Report

BEAMPATH

User Manual

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Abstract

BEAMPATH is a 2D and 3D code for simulation of space charge dominated beam dynamics in linear particle accelerators and beam transport. The program is used for particle-in-cell simulation of axial-symmetric, quadrupole-symmetric and z-uniform beams in a channel containing RF gaps, radio-frequency quadrupoles, multipole lenses, solenoids, bending magnets, accelerating waveguides. Detailed description of model can be found in Ref. [1]

1.0 Installation and run

Compiler

Download GNU 4.2.3 Fortran compiler from http://r.research.att.com/tools/. Other compilers (Absoft Fortran) also can be used.

Source code

Source directory *beampath_source* contain Fortran source of the code and file *Makefile*. In terminal window, type *make* to generate executable file *beampath.exe*.

Execution of the code

Put in the same directory executable file *beampath.exe* and file *beampath* containing initial data of the problem. In terminal window, type *./beampath.exe* and press *Enter* to start the program. Execution of the program can be observed at the terminal window via constantly changing lines with beam parameters. To start a new problem, all files generated by the code during previous run, have to be removed from the directory. Start new run with *beampath.exe* and *beampath* files only in one directory.

Code output

During execution, code generates new files with beam parameters, particle coordinates and momentum, and field data. Open files with any of graphics program for plotting the graphics. Recommended graphics software: Pro Fit from http://www.quansoft.com/.

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[1] Y.K.Batygin, "Particle-in-cell code BEAMPATH for beam dynamics simulations in linear accelerators and beamlines" Nuclear Instruments and Methods in Physics Research A 539 (2005) 455–489.

2.0 File beampath (initial data)

Initial data of the problem are in the file BEAMPATH. It contains sequence of FORTRAN namelist statements starting with symbol $ and the name of the namelist (for example, $BEAM), end ends with $END. Between namelists, there should be 5 empty lines where any information might be printed, usually the name of namelist. At the end of the manual, there is an example of beampath file.

Beginning of the beampath file

2.1 Name of the Problem

NAME OF THE PROBLEM (no more than 50 symbols)

2.2 Beam Parameters

$BEAM

IDIM Symmetry of the beam for space charge calculations

= 'RZ' - axial symmetric beam

= 'QZ' - quadrupole symmetric beam (default)

= 'XY' - z-uniform beam

WAVE RF wavelength (cm), must be positive. For IDIM = 'XY', parameter WAVE is arbitrary.

A Atomic mass of particles (must be positive, for protons A = 1, for electrons A = 0.544E-03)

IZ Charge of the particles (must be integer, both positive and negative, for example, for proton IZ=1)

NPART Number of modeling particles (integer, default = 1)

CURR Beam current, Ampere (default = 0)

NSTEP Number of integration steps per RF period (recommended values: 10…..100)

T0 Initial dimensionless moment of time (in scale of RF period)

TFIN Final dimensionless moment of time (in scale of RF period)

Z0 Initial coordinate of the center of the bunch (cm)

IDEBG = .TRUE. Print debugging information in beampath_data file

= .FALSE. No print debugging information in beampath_data file

IDEBG=T, generates large output of debugging information. Normally it is not worth to do it.

IQX Defines number of x-mesh: $N_X=2^{IQX}$

IQY Defines number of y-mesh: $N_Y=2^{IQY}$

IQZ Defines number of z-mesh: $N_Z=2^{IQZ}$

For 3D simulations IDIM='QZ', the mesh is limited by IQX ≤10, IQY ≤10, IQZ ≤10

NREP Renew space charge forces every NREP steps (default = 1)

VX= $\frac{4}{mc}\sqrt{<x^2><P_x^2>-<xP_x>^2}$ Normalized 4 rms beam emittance on (x-P_x) phase plane (π cm mrad),

must be VX > 0

VY= $\frac{4}{mc}\sqrt{<y^2><P_y^2>-<yP_y>^2}$ Normalized 4 rms beam emittance on (y-P_y) phase planes, (π cm*mrad),

must be VY > 0

$RX = 2\sqrt{<x^2>} = \sqrt{\beta_x \mathrm{E}_x}$ Beam envelope in x-direction, two rms beam size, (cm), where β_x is the Twiss parameter and $\mathrm{E}_x = 4\sqrt{<x^2><x'^2> - <xx'>^2} = \dfrac{VX}{PZ0}$ is the natural beam emittance

$RY = 2\sqrt{<y^2>} = \sqrt{\beta_y \mathrm{E}_y}$ Beam envelope in y-direction, two rms beam size (cm), where β_y is the Twiss parameter and $\mathrm{E}_y = 4\sqrt{<y^2><y'^2> - <yy'>^2} = \dfrac{VY}{PZ0}$ is the natural beam emittance

$DRXDZ = -\alpha_x\sqrt{\dfrac{\mathrm{E}_x}{\beta_x}}$ Slope of beam x- envelope to z-axis (radian), where α_x, is the Twiss parameter, and $E_x = \dfrac{VX}{PZ0}$ is the natural beam emittance

$DRXDZ = -\alpha_y\sqrt{\dfrac{\mathrm{E}_y}{\beta_y}}$ Slope of beam y- envelope to z-axis (radian), where α_y, is the Twiss parameter, and $E_y = \dfrac{VY}{PZ0}$ is the natural beam emittance

ITYPE Type of the phase space distribution
- = 'KV' (Kapchinsky - Vladimirsky)
- = 'WB' 'Water Bag'
- = 'GS' Gaussian
- = 'PB' Parabolic

DX Displacement of the beam centroid in x-direction, cm (default = 0)

DY Displacement of the beam centroid in y-direction, cm (default = 0)

DXDZ Slope of the beam axis in x-direction, radian (default = 0)

DYDZ Slope of the beam axis to y-direction, radian (default = 0)

PZ0 Initial dimensionless z-momentum of the beam (divided by *mc*) $PZ0 = p_z/mc$

DPZ Total spread of the z-momentum of the beam divided by initial z-momentum of the bunch, $\Delta p_z/ PZ0$

BUNCH Length of the bunch in RF scale, BUNCH = $L_{bunch}/\beta\lambda$

DPZDZ Slope of longitudinal beam envelope in $(z, dp_z/p_z)$

$END

2.3 Aperture

$APERT

N Number of z-points (cm)

ZAPERT(N) Longitudinal coordinates (cm)

XAPERT(N) Radius of x – aperture (cm)

YAPERT(N) Radius of y – aperture (cm)

IAPER = .TRUE. (default) Values of aperture will be used along the channel
= .FALSE. Values of aperture will be substituted by aperture data in DTL and RFQ

$END

2.4 Initial Coordinates, Momentum, and Polarization of Particles

$PARTIC

User can specify initial coordinates, momentum, and spin components of particles, which substitute the values generated by previous parameters in $BEAM. Number of substituted particles must be equal or less than number of modeling particles NPART. If no substitution is required, this namelist is empty.

X (NPART)	Initial x- coordinates of particles, cm, defined by the user
Y (NPART)	Initial y- coordinates of particles, cm, defined by the user
Z (NPART)	Initial z- coordinates of particles, cm, defined by the user
PX(NPART)	Initial reduced x-momentum of the particles, defined by the user
PY(NPART)	Initial reduced y-momentum of the particles, defined by the user
PZ(NPART)	Initial reduced z-momentum of the particles, defined by the user
SX(NPART)	Initial x-component of particle spin
SY(NPART)	Initial y-component of particle spin
SZ(NPART)	Initial z-component of particle spin
POLARIZATION(NPART)	Polarization of particle

$END

2.5 Output parameters

$OUTPUT

NOUT Interval in recording of particle positions:

= 0 no record

= 1 record every time step

= 2 record every other time step, etc.

Created files are labeled "1001", "1002", "1003",…

IPART Number of first IPART particles, which trajectories are stored in file TRAJECT

NREC Interval in recording of trajectories of IPART particles in file TRAJECT

= 0 no record of trajectories

= 1 record of IPART trajectories at every time step

= 2 record of IPART trajectories at every other time step,

ITRAJ = .TRUE. – Coordinates and momentum of first IPART particles will be printed in file BEAMPATH_DATA at every time step

= .FALSE.- No prints of coordinates and momentum of IPART particles

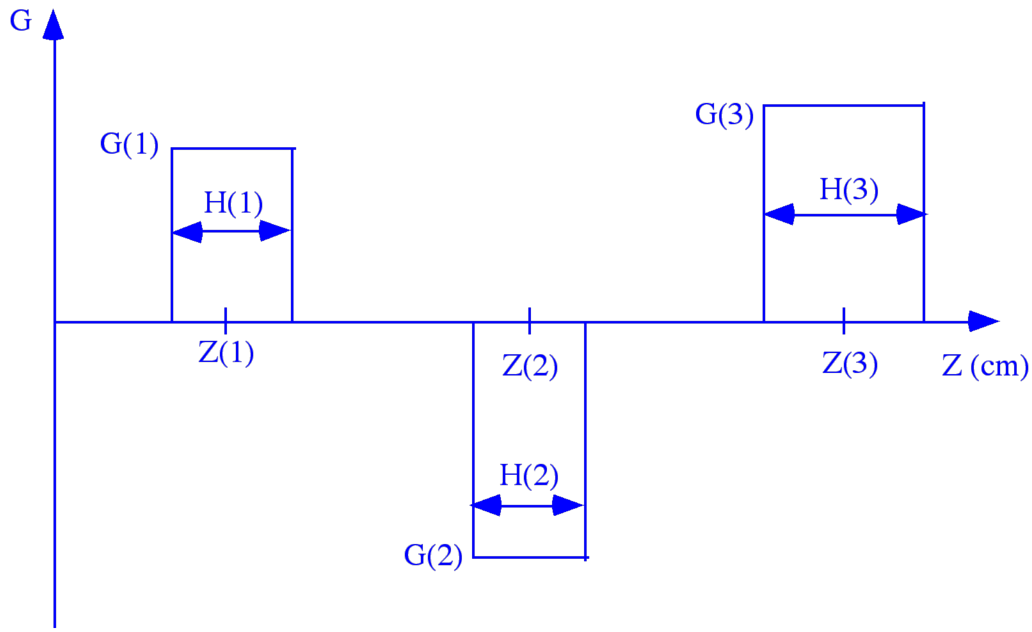
NPLANE Number of z-points to store particle positions

ZPLANE(NPLANE) z-coordinates to store particle positions (cm)

Distance between subsequent ZPLANE (I) must be larger than $\beta\lambda$

$END

2.6 Multipole Lenses



Specification of multipole lenses parameters for FIELD= 'IDEAL'.

$MULT

FIELD	= 'IDEAL' - if ideal multipoles are specified (default)
	= 'GRID' - if field components are specified in grid points

The following parameters must be specified if FIELD = 'IDEAL'

N	Number of multipole lenses (default = 0)
TYPEL (N)	= 'ELEC' - for electrostatic lens
	= 'MAGN' - for magnet lens
NRD(N)	Order of multipole field (2 for quadrupoles, 3 for sextupoles, etc.)
Z(N)	z - positions of the center of lenses (cm)
H(N)	Length of lenses, cm (default = 0)
G(N)	Field strength (default = 0)

$$G(N) = \frac{Electric\ \ Pole\ \ Field}{(Pole\ \ Raius)^{NRD}}[\frac{kV}{cm^{NRD}}]$$ for electrostatic lens

$$G(N) = \frac{Magnetic\ \ Pole\ \ Field}{(Pole\ \ Raius)^{NRD-1}}[\frac{Tesla}{cm^{NRD-1}}]$$ for magnetic lens

TILT(N)	Roll angle around longitudinal axis, radian (default = 0)
DX(N)	x - displacement of the lenses from the axis, cm (default = 0)
DY(N)	y - displacement of the lenses from the axis, cm (default = 0)

The following parameters must be specified if FIELD = 'GRID'

NX	Number of grid points in x
NY	Number of grid points in y
NZ	Number of grid points in z
XGRID(NX)	Coordinates of grid points in x (cm)
YGRID(NX)	Coordinates of grid points in y (cm)
ZGRID(NX)	Coordinates of grid points in z (cm
BX(NX*NY*NZ)	One dimensional array of B_x component (Tesla)
BY(NX*NY*NZ)	One dimensional array of B_y component (Tesla)
BZ(NX*NY*NZ)	One dimensional array of B_z component (Tesla)
EX(NX*NY*NZ)	One dimensional arrays of E_x component (kV/cm)
EY(NX*NY*NZ)	One dimensional arrays of E_y component (kV/cm)
EZ(NX*NY*NZ)	One dimensional arrays of E_z component (kV/cm)

*All arrays are one-dimensional, where index is the most fast in X, then in Y, and then (the most slow) in Z. For grid point with position XGRID(I), YGRID(J), ZGRID(K), the array number is NUMBER(I,J,K)=(K-1)*NY*NX + (J-1)*NX + I*

Field map is printed in file multipole_field_mesh

$END

2.7 Solenoid

$SOLEN

NSOLEN	Number of points
ZSOLEN(NSOLEN)	Longitudinal coordinates (cm)
BSOLEN(NSOLEN)	Longitudinal magnetic field of the solenoid (Tesla)
NSCR	= .TRUE. - cathode is shielded from magnetic field (all particles get additional rotation
	= .FALSE.- cathode is not shielded from magnetic field

In case the values of magnetic field have to be multiplied by constant value, use additional program z_Bz_Table_BEAMPATH to scale the values of BSOLEN (NSOLEN).

Fringe field has to be specified as a function BSOLEN(ZSOLEN). The common way is to use 4-points model, for example:

ZSOLEN= 0 1 10. 11

BSOLEN= 0 0.3 0.3 0

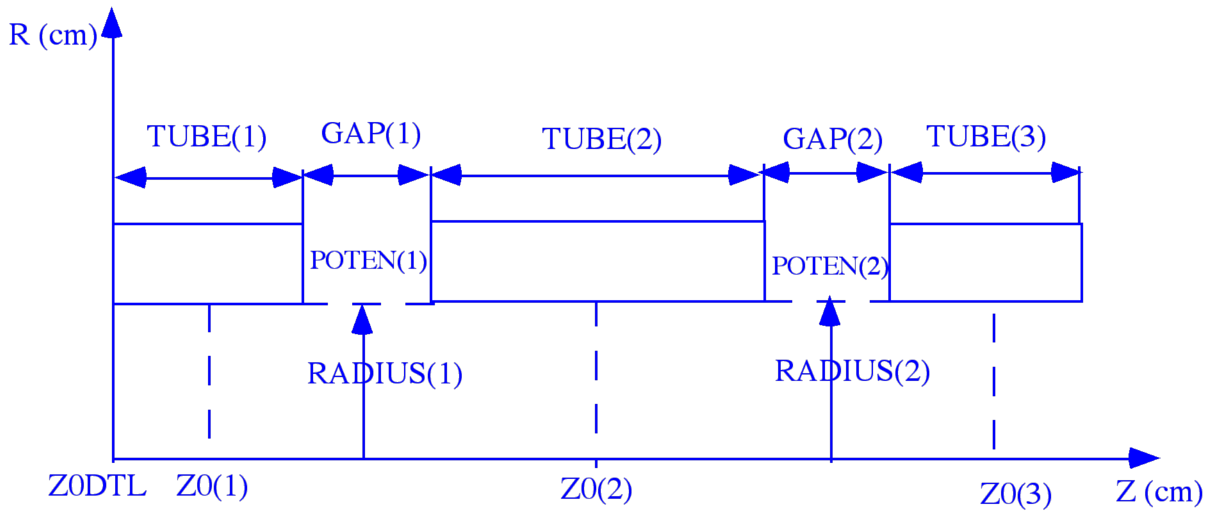
The range of fringe field (in this example Fringe_z= 1cm) should be sufficiently larger than integration step:

$$Fringe\_z >> \frac{P_z}{\gamma} \cdot \frac{WAVE}{NSTEP}$$

Good check is beam dynamics run through solenoid without space charge. Beam emittance should be kept constant. If not, reduce integration step (increase NSTEP).

$END

2.8 RF Gaps



Definition of RF gap parameters.

The electromagnetic field at every gap is presented as Fourier-Bessel expansion:

$$E_z(z,r,t) = -\cos(\omega t + \varphi_o) \sum_{m=1}^{M} E_m I_o(\mu_m r) \sin\left(\frac{2\pi m z}{L}\right)$$

$$E_r(z,r,t) = \cos(\omega t + \varphi_o) \sum_{m=1}^{M} E_m \frac{2\pi m}{\mu_m L} I_1(\mu_m r) \cos\left(\frac{2\pi m z}{L}\right)$$

$$B_\theta(z,r,t) = \frac{1}{c} \sin(\omega t + \varphi_o) \sum_{m=1}^{M} E_m \frac{2\pi}{\mu_m \lambda} I_1(\mu_m r) \sin\left(\frac{2\pi m z}{L}\right)$$

$$\mu_m = \frac{2\pi}{\lambda}\sqrt{\left(\frac{m\lambda}{L}\right)^2 - 1}$$

$DTL

FIELD	= 'POTEN' If the potential differences between drift tubes are specified
	=' EGAP' If the value of electric field in the center of every gap at the axis are specified
	= 'HARM' If Fourier harmonics of the field expansion at every gap are specified
	= 'EZAP' if Ez field is given at the aperture boundary of the gap
IFIELD	= .TRUE. Plot E_z, E_r field in every gap
	= .FALSE. No plots of E_z, E_r in every gap
NGAP	Number of gaps between drift tubes
NHARM	Number of Fourier harmonics of the field expansion in every gap
Z0DTL	Longitudinal coordinate of the beginning of the DTL structure (cm)
VIBRAD	Vibrator radius of resonator, cm (default = 0)

VIBDIS	Distance between vibrators, cm (default = 0)
TUBE (NGAP)	Lengths of the drift tubes (cm)
GAP (NGAP)	Gaps between drift tubes (cm)
RADIUS (NGAP)	Radius of aperture at the gap (cm)
BETA (NGAP)	Velocity of synchronous particle (divided by *c*) at the center of each gap
EGAP (NGAP)	Electric field in the center of every gap at the axis of structure (kV/cm) (for FIELD='EGAP')
POTEN (NGAP)	Potential difference between drift tubes (kV) (for FIELD = 'POTEN')
PHASE (NGAP)	Initial RF phase in the gaps, φ_o, (radian)

*The values of PHASE (NGAP) are phases of RF field at the initial moment of time T0. At the time T when particles arrive to RF gap, the phase in each gap is 2π*T*KFREQ(I) + PHASE(I).*
*For bunchers, PHASE(I)=1.57079 - 2π*T_s*KFREQ(I), where T_s*
is the time of arrival of the synchronous particle to the center of the gap.

KFREQ(NGAP)	Multiple RF frequency factor (default =1), equal to 1 or more (2, 3 , 4...)
DXDTL (NGAP)	x-displacement of the gap (cm)
DYDTL (NGAP)	y-displacement of the gap (cm)

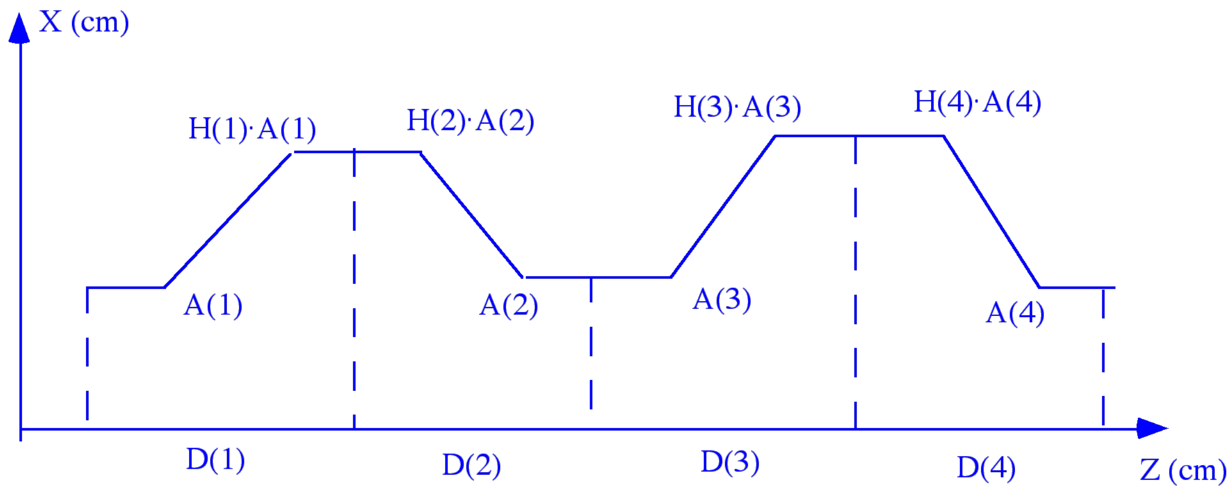
The following parameters must be specified if FIELD = 'HARM'

Z0(NGAP+1)	Boundaries of the gaps (cm)
W (NGAP)	Wave numbers (cm^{-1})
E (NGAP*NHARM)	Fourier harmonics amplitudes of the field expansion at every gap (kV/cm)
ANGLE (NGAP*NHARM)	Fourier harmonics phases of the field expansion at every gap (radian)

The following parameters must be specified if FIELD = 'EZAP'

Z0(NGAP+1)	Boundaries of the gaps (cm)
EZAPER(NGAP*NHARM)	E_z field (kV/cm) at the aperture of the channel at the equidistant points except points Z0(I).

2.9 Radio Frequency Quadrupole



Definition of RFQ parameters.

The RFQ field in the i-th cell of the structure is given by:

$$E_x = \frac{U_L}{a}\left[\chi \frac{x}{a} + (-1)^i 4T\, I_1(\mu_1 r)\left(\frac{a}{\beta\lambda}\right)\left(\frac{x}{r}\right)\sin(\mu_1 z)\right]\cos(\omega t+\varphi_o)$$

$$E_y = \frac{U_L}{a}\left[-\chi \frac{y}{a} + (-1)^i 4T\, I_1(\mu_1 r)\left(\frac{a}{\beta\lambda}\right)\left(\frac{y}{r}\right)\sin(\mu_1 z)\right]\cos(\omega t+\varphi_o)$$

$$E_z = 4\frac{U_L}{\beta\lambda}(-1)^i\, T\, I_o(\mu_1 r)\cos(\mu_1 z)\cos(\omega t+\varphi_o)\,, \qquad \mu_1 = \frac{2\pi}{\beta\lambda}$$

$RFQ

N Number of the RFQ cells length of length *$\beta\lambda/2$*

FIELD = 'PARMTEQ' (default) RFQ field is calculated as a linear variation of acceleration efficiency, focusing efficiency, and aperture of the channel along the structure. All values are assigned at the end of each cell.

='STEP' RFQ field is calculated as a step-wise function of given parameters. All parameters are constant at the cell length.

ELECTRODE = 'IDEAL' (default) Accelerating and focusing terms are calculated using analytical formulas for ideal electrode shape:

$$T = \frac{\pi}{4}\frac{m^2-1}{m^2 I_o(ka) + I_o(mka)} \qquad\qquad \chi = 1 - \frac{4T}{\pi} I_o(ka)$$

= 'REAL' Accelerating and focusing terms are defined by arrays T_REAL(N), CAPPA_REAL(N)

Z0 Starting coordinate of RFQ structure, cm

IFIELD = .TRUE. Plot axial voltage and focusing gradient along the structure in newly created files rfq_FOCUS_GRADIENT, rfq_UT_rfq

= .FALSE. No plots of RFQ field (default='FALSE')

D(N) Length of the rfq cells (cm)

U(N) Potential differences between electrodes (kV)

BETA(N) Velocity of synchronous particle (divided by *c*)

A(N) Radius of aperture, cm

H(N) Modulation of the electrodes

K(N) Multiple RF frequency factor

PHASE(N) Initial RF phase in the RFQ cells (radian)

*The values PHASE(I) define RF phases in cells at the initial moment of time 2π*T0*K(I) + PHASE(I)*

*At the time T when particles arrive to RFQ, the value of phases are 2π*T*K(I) + PHASE(I).*

DX(N) X-displacement of RFQ cells (cm)

DY(N) Y-displacement of RFQ cells (cm)

ERROR Error in RFQ geometry (cm)

The following parameters must be specified if ELECTRODE = 'REAL'

T_REAL(N) Efficiency of RFQ acceleration of real electrodes

CAPPA_REAL(N) Efficiency of RFQ focusing of real electrodes

Parameters T_REAL, CAPPA_REAL are connected with PARMTEQ field coefficients A_{10}, A_o via:

$$T\_REAL = \frac{\pi}{4}A_{10} \qquad CAPPA\_REAL = A_o\frac{a^2}{R_o^2} = A_o\chi \qquad R_o = \frac{a}{\sqrt{1-\frac{4T}{\pi}I_o(ka)}}$$

where R_o is the distance from the axis to electrodes at the cross section with exact quadrupole symmetry

$END

2.10 User Defined Element

$USER

User defined element is defined in subroutine EXT5.FOR. Electric and magnetic fields have to be added to other fields:

EX(I)= EX(I) + USER DEFINED EX-FIELD (KV/CM)

EY(I)= EY(I) + USER DEFINED EY-FIELD (KV/CM)

EZ(I)= EZ(I) + USER DEFINED EZ-FIELD (KV/CM)

BX(I)= BX(I) + USER DEFINED BX-FIELD (TESLA)

BY(I)= BY(I) + USER DEFINED BY-FIELD (TESLA)

BZ(I)= BZ(I) + USER DEFINED BZ-FIELD (TESLA)

$END

2.11 2D Map of Axial-Symmetric Magnetic Field

$MAGNET_LENS

NZ	Number of points in z
NR	Number of points in r
Z(NZ)	Longitudinal coordinates (cm)
R(NR)	Radial coordinates (cm)
IFIELD	= .TRUE. (default) print $B_Z(z, r)$ and $B_r(z, r)$ in files MAGNET_LENS_BZ and
	MAGNET_LENS_BR at three different radii *r = R(NR)/3, r= 0.66*R(NR), r=R(NR)*
	= .FALSE. no prints
BZ(NZ*NR)	Longitudinal magnetic field (Tesla)
BR(NZ*NR)	Transversal magnetic field (Tesla)

Both BZ and BR are one-dimensional arrays in the following order:
BZ(Z1,R1), BZ(Z1,R2), BZ(Z1,R3),...BZ(Z1,NR),
BZ(Z2,R1), BZ(Z2,R2), BZ(Z2,R3),...BZ(Z2,NR),
....
BZ(NZ,R1), BZ(NZ,R2), BZ(NZ,R3),...BZ(NZ,NR)
the same for BR. The steps in Z and R are arbitrary.

Entire map $B_Z(z, r)$, $B_r(z, r)$ is printed in file magnetic_field_2D_map

$END

2.12 Bending Magnets

$BEND

The magnetic field inside a bending magnet is described by the Taylor expansion up to the terms of second order:

$$B_x(x,y,z) = B_y \left(- n \frac{y}{R} + 2\xi \frac{xy}{R^2}\right)$$

$$B_y(x,y,z) = B_y \left[1 - n \frac{x}{R} + \frac{n}{2}\frac{y^2}{R^2} + \xi \frac{(x^2 - y^2)}{R^2}\right]$$

where B_y is the vertical component of magnetic field along the reference trajectory with radius of curvature R, n is the field index and ξ is a nonlinear coefficient in the magnetic field expansion:

$$n = - \left[\frac{R}{B_y}\frac{\partial B_y}{\partial x}\right]_{x=0,y=0} \qquad \xi = \left[\frac{R^2}{2!\, B_y}\frac{\partial^2 B_y}{\partial x^2}\right]_{x=0,y=0}$$

At the entrance and at the exit of the magnet, the slope of the particle trajectory is changed because of the pole angle α according to the linear matrix transformation

$$\begin{vmatrix} x \\ x' \\ y \\ y' \end{vmatrix} = \begin{vmatrix} 1 & 0 & 0 & 0 \\ \frac{tg\alpha}{R} & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & -\frac{tg(\alpha - \psi)}{R} & 1 \end{vmatrix} \begin{vmatrix} x_o \\ x'_o \\ y_o \\ y'_o \end{vmatrix}$$

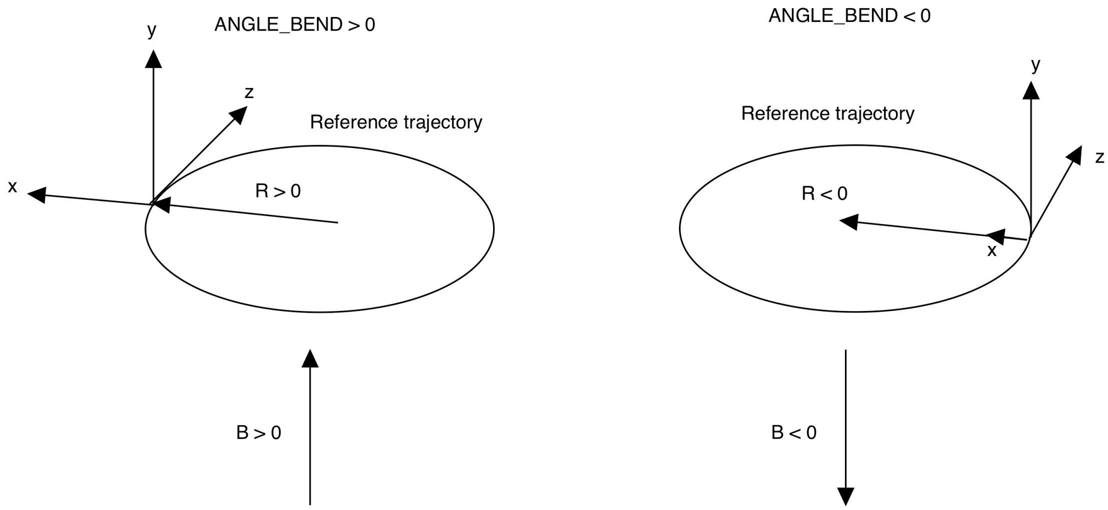
The correction angle ψ is given by the expression

$$\psi = K_1 \left(\frac{g}{R}\right) \left(\frac{1+\sin^2\alpha}{\cos \alpha}\right) \left[1- K_1 K_2 \left(\frac{g}{R}\right) tg\alpha\right]$$

where g is the gap of the magnet and coefficients K_1, K_2 are defined by pole geometry.

Parameters K_1, K_2 defined for different model of fringing field

Model	K_1	K_2
Square-edged magnet	0.45	2.8
Linear	1/6	3.8
Clamped Rogowski	0.4	4.4
Unclamped Rogowski	0.7	4.4



Definition of magnetic field in bending magnet.

N	Number of bending magnets
Z(N)	Longitudinal coordinate of the center of magnet (cm)
B(N)	Vertical component of magnetic field (Tesla)
R(N)	Radius of curvature (cm)
ANGLE_BEND(N)	Angle of bend of reference particle in magnet (degrees)
COEFF1(N)	Field index, n
COEFF2(N)	Nonlinear coefficient in the magnetic field expansion, ξ
GAP(N)	Gap of the magnet, g (cm)
ANGLE_IN(N)	Pole angle of the beam at the entrance of the magnet (degrees)
ANGLE_OUT(N)	Pole angle of the beam at the exit of the magnet (degrees)

Negative values of ANGLE_IN(I), ANGLE_OUT(I) for positive curvature radius R(I)>0 correspond to edge focusing in x-direction (y-defocusing)

AK1(N)	Fringing field coefficient, K_1
AK2(N)	Fringing field coefficient, K_2

$END

2.13 Accelerating Waveguide

$WAVEGUIDE

N	Number of points
Z0(N)	Longitudinal coordinates (cm)
E(N)	Accelerating field (kV/cm)
PS(N)	Longitudinal momentum of synchronous particle (divided by *mc*)
PHASE(N)	Synchronous phase (radian)

$END

2.14 RFQ for Beam Funneling

$RFQ_FUNNELING

Defines modified RFQ structure to combine two beams in one beam [R. H. Stokes and G. N. Minerbo, AIP Conference Proceedings 139 (1985), p. 79.] The electrode configuration is changed with respect to conventional RFQ to provide additional dipole component of electric field.

N	Number of the RFQ cells length of length $\beta\lambda/2$
Z0	Starting coordinate of RFQ structure (cm)
ZMAX	End coordinate of RFQ structure (cm)
	IFIELD = .TRUE. print axial voltage and focusing gradient along the structure in newly created files FOCUS_GRADIENT_rfq.RES, UT_rfq.RES
	= .FALSE. no prints
D(N)	Length of the rfq cells (cm)
U(N)	Potential differences between electrodes (kV)
BETA(N)	Velocity of synchronous particle (divided by *c*)
A(N)	Radius of aperture (cm)
H(N)	Modulation of the electrodes
K(N)	Multiple RF frequency factor
PHASE(N)	Initial RF phase in the RFQ cells (radian)
DX(N)	X-displacement of RFQ cells (cm)
DY(N)	Y-displacement of RFQ cells (cm)
ERROR	Error in RFQ geometry (cm)
SHIFT_ELECTRODE	Shift of RFQ electrodes (cm)

$END

2.15 2D RF Deflector

$RF_DEFLECTOR_2D

Defines 2D RF field which is calculated as

E_y = EY_TW* COEFF*cos(2πT + PHASE0)

E_z = EZ_TW* COEFF *cos(2πT + PHASE0)

NZ	Number of points in z direction
NY	Number of points in y-direction
ZGRID (NZ)	Coordinates of mesh in z-direction, cm
YGRID (NY)	Coordinates of mesh in y-direction, cm
EZ_TW (NZ*NY)	E_z field in mesh points, kV/cm
EY_TW (NZ*NY)	E_y field in mesh points, kV/cm
COEFF	Field amplitude coefficient
PHASE0	Initial phase of the field at the moment T0, radian

Both EZ_TW and EY_TW are one-dimensional arrays in the order where z is changing faster than y:

EZ_TW (Y1,Z1), EZ_TW (Y1,Z2), EZ_TW (Y1,Z3),... EZ_TW (Y1,NZ),

the same for EY_TW

$END

2.16 3D RF Deflector

$RF_DEFLECTOR_3D

Defines 3D RF field which is calculated as

E_x = EX_GRID*COEFF*cos(2πT + PHASE0)

E_y = EY_GRID*COEF*cos(2πT + PHASE0)

E_z = EZ_GRID*COEFF*cos(2πT + PHASE0)

NX_EX	Number of mesh points in x-direction for E_x field
NX_EY	Number of mesh points in x-direction for E_y field
NX_EZ	Number of mesh points in x-direction for E_z field
NY_EX	Number of mesh points in y-direction for E_x field
NY_EY	Number of mesh points in y-direction for E_y field
NY_EZ	Number of mesh points in y-direction for E_z field
NZ_EX	Number of mesh points in z-direction for E_x field
NZ_EY	Number of mesh points in z-direction for E_y field

NZ_EZ	Number of mesh points in z-direction for E_z field
XGRID_EX	Coordinates of mesh in x-direction for E_x field (cm)
YGRID_EX	Coordinates of mesh in y-direction for E_x field (cm)
ZGRID_EX	Coordinates of mesh in z-direction for E_x field (cm)
XGRID_EY	Coordinates of mesh in x-direction for E_y field (cm)
YGRID_EY	Coordinates of mesh in y-direction for E_y field (cm)
ZGRID_EY	Coordinates of mesh in z-direction for E_y field (cm)
XGRID_EZ	Coordinates of mesh in x-direction for E_z field (cm)
YGRID_EZ	Coordinates of mesh in y-direction for E_z field (cm)
ZGRID_EZ	Coordinates of mesh in z-direction for E_z field (cm)
EX_GRID	E_x field in mesh points (kV/cm)
EY_GRID	E_y field in mesh points (kV/cm)
Ez_GRID	E_z field in mesh points (kV/cm)
COEFF	Field amplitude coefficient
PHASE0	Initial phase of the field at the moment T0 (radian)

Field components are one-dimensional arrays, where fastest coordinate is x, then y, then z

$END

2.17 Axial-Symmetric Electrostatic Field

$ELECTROSTATIC_2D

NZ	Number of points in z
NR	Number of points in r
Z(NZ)	Longitudinal coordinates (cm)
R(NR)	Radial coordinates (cm)
EZ(NZ*NR)	Longitudinal electrostatic field (kV/cm)
ER(NZ*NR)	Radial electrostatic field (kV/cm)
COEFF	Scaling coefficient. Field components acting at particles are COEFF* EZ, COEFF*ER

Both EZ and ER are one-dimensional arrays in the following order:

EZ(Z1,R1), EZ(Z1,R2), EZ(Z1,R3),...EZ(Z1,NR),

EZ(Z2,R1), EZ(Z2,R2), EZ(Z2,R3),...EZ(Z2,NR),

....

EZ(NZ,R1), EZ(NZ,R2), EZ(NZ,R3),...EZ(NZ,NR)

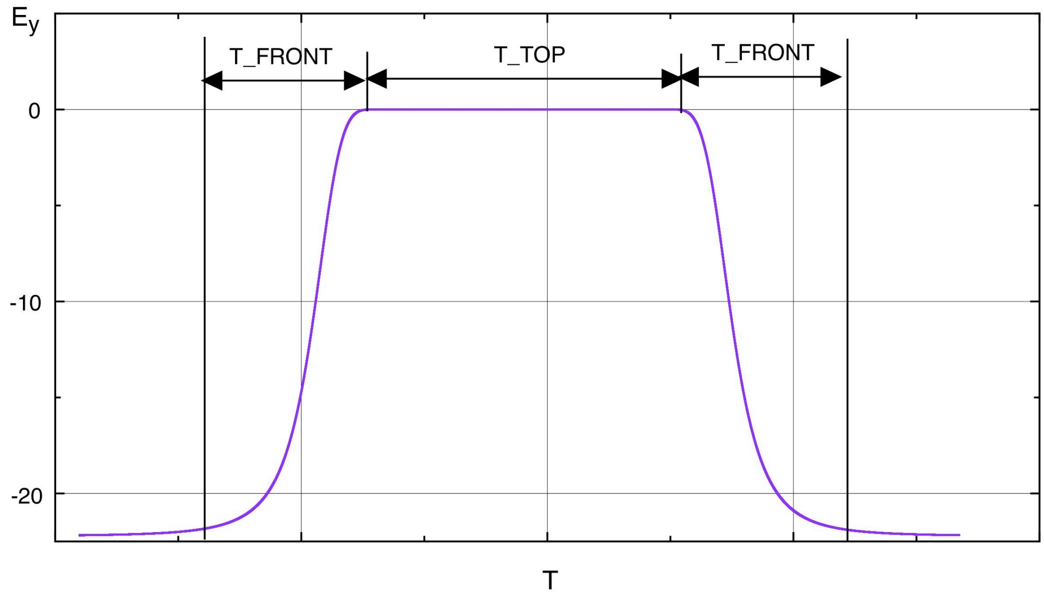
the same for ER. The steps in z and r are arbitrary.

*Field map components COEFF*EZ(NZ*NR), COEFF*ER(NZ*NR) are printed in file electrostatic_ez_er.*

*Interpolated field components COEFF*EZ(z,r), COEFF*ER(z,r) at radii r = R(NR)/3, R(NR)*(2/3), R(NR) are printed in file electrostatic_ez_er_3curves.*

$END

2.18 Chopper



Chopper pulse

Chopper is represented as a pulse of Ey component propagating within the chopper length:

Z0_Chopper < z < Z0_Chopper+ Chopper_length

Chopper pulse is a traveling wave pulse dependent of variable

$$\xi = (Z - Z\_INITIAL) - BETA\_CHOPPER * c * (T - T\_INITIAL)$$

Chopper field is described by equations:

$$E_y(\xi) = E_o[1 - \frac{1}{1 + 32(\frac{\xi - \xi_{front}}{\xi_{front}})^4}], \quad 0 < \xi < \xi_{front}$$

$$E_y(\xi) = 0, \qquad \xi_{front} \le \xi \le \xi_{front} + \xi_{top}$$

$$E_y(\xi) = E_o[1 - \frac{1}{1 + 32(\frac{\xi - \xi_{front} - \xi_{top}}{\xi_{front}})^4}], \quad \xi > \xi_{front} + \xi_{top}$$

Z0_CHOPPER	Initial coordinate of chopper (cm)
CHOPPER_LENGTH	Length of chopper (cm)
T_FRONT	Time of head and tail front
T_TOP	Time of flat part of pulse
CHOPPER_VOLTAGE	Voltage between chopper plates (kV)
GAP_ENTRANCE	Entrance y-gap of the chopper (cm)
GAP_EXIT	Exit y-gap of the chopper (cm)
T_INITIAL	Initial moment of time for chopper pulse
Z_INITIAL	Initial position of chopper pulse in z (cm)
BETA_CHOPPER	Velocity of chopper pulse

$END

2.19 Multi - Harmonic Buncher

This section is similar to DTL. Field is calculated as

$$E_z(z,r,t) = -\sum E_m I_0(\mu_m r)\sin(\frac{2\pi mz}{L})$$
$$[A_1\cos(\omega t+\varphi o)+A_2\cos(2\omega t+\varphi o)+A_3\cos(3\omega t+\varphi o)+A_4\cos(4\omega t+\varphi o)+$$
$$A_5\cos(5\omega t+\varphi o)+A_6\cos(6\omega t+\varphi o)+A_7\cos(7\omega t+\varphi o)+A_8\cos(8\omega t+\varphi o)+$$
$$A_9\cos(9\omega t+\varphi o)+A_{10}\cos(10\omega t+\varphi o)]$$

Other components E_r, B_θ are calculated accordingly.

$MHB

AMPLITUDE (10)	Dimensionless amplitudes of harmonics in each gap
FIELD	= 'POTEN' if the potential differences between drift tubes are specified
	=' EGAP' if the value of electric field in the center of every gap at the axis are specified
	= 'HARM' if Fourier harmonics of the field expansion at every gap are specified
	= 'EZAP' if Ez field is given at the aperture boundary of the gap
IFIELD	= .TRUE. Plot E_z, E_r field in every gap
	= .FALSE. No plots of E_z, E_r in every gap
NGAP	Number of gaps between drift tubes
NHARM	Number of Fourier harmonics of the field expansion in every gap
Z0DTL	Longitudinal coordinate of the beginning of the DTL structure (cm)
VIBRAD	Vibrator radius of resonator, cm (default = 0)
VIBDIS	Distance between vibrators, cm (default = 0)
TUBE (NGAP)	Lengths of the drift tubes (cm)
GAP (NGAP)	Gaps between drift tubes (cm)
RADIUS (NGAP)	Radius of aperture at the gap (cm)
BETA (NGAP)	Velocity of synchronous particle (divided by *c*) at the center of each gap
EGAP (NGAP)	Electric field in the center of every gap at the axis of structure (kV/cm) (for FIELD='EGAP')
POTEN (NGAP)	Potential difference between drift tubes (kV) (for FIELD = 'POTEN')
PHASE (NGAP)	Initial RF phase in the gaps, φ_o, (radian)

*The values of PHASE (NGAP) are phases of RF field at the initial moment of time T0. At the time T when particles arrive to RF gap, the phase in each gap is 2π*T*KFREQ(I) + PHASE(I)*

KFREQ(NGAP)	Multiple RF frequency factor (default =1), equal to 1 or more (2, 3 , 4...)
DXDTL (NGAP)	x-displacement of the gap (cm)

DYDTL (NGAP)	y-displacement of the gap (cm)

The following parameters must be specified if FIELD = 'HARM'

Z0(NGAP+1)	Boundaries of the gaps (cm)
W (NGAP)	Wave numbers (cm^{-1})
E (NGAP*NHARM)	Fourier harmonics amplitudes of the field expansion at every gap (kV/cm)
ANGLE (NGAP*NHARM)	Fourier harmonics phases of the field expansion at every gap (radian)

The following parameters must be specified if FIELD = 'EZAP'

Z0(NGAP+1)	Boundaries of the gaps (cm)
EZAPER(NGAP*NHARM)	E_z field (kV/cm) at the aperture of the channel at the equidistant points except points Z0(I).

$END

2.20 3D RF Mesh Field

&MESH_RF_1

Defines 3D RF field which is calculated as

E_x = EX_GRID*COEFF*cos(2πT*KFRQ + PHASE0)

E_y = EY_GRID*COEF*cos(2πT*KFRQ + PHASE0)

E_z = EZ_GRID*COEFF*cos(2πT*KFRQ + PHASE0)

B_x = -BX_GRID*COEFF*sin(2πT*KFRQ + PHASE0)

B_y = -BY_GRID*COEF*sin(2πT*KFRQ + PHASE0)

B_z = -BZ_GRID*COEFF*sin(2πT*KFRQ + PHASE0)

Maximum mesh is defined in EXT21.FOR

parameter (nxmax=30)
parameter (nymax=30)
parameter (nzmax=300)

NX	Number of mesh points in x-direction
NY	Number of mesh points in y-direction
NZ	Number of mesh points in z-direction
XGRID	Coordinates of mesh in x-direction (cm)
YGRID	Coordinates of mesh in y-direction (cm)
ZGRID	Coordinates of mesh in z-direction (cm)
EX_GRID	E_x field in mesh points (kV/cm)
EY_GRID	E_y field in mesh points (kV/cm)
EZ_GRID	E_z field in mesh points (kV/cm)
BX_GRID	B_x field in mesh points (Tesla)
BY_GRID	B_y field in mesh points (Tesla)
BZ_GRID	B_z field in mesh points (Tesla)
COEFF	Field amplitude coefficient
PHASE0	Initial phase of the field at the moment T0 (radian)
KFREQ	Multiple RF frequency factor (default =1), equal to 1 or more (2, 3 , 4...)

Field components are one-dimensional arrays, where fastest coordinate is in x, then y, then z

&END

There are additional 3D RF field meshes with the similar data as MESH_RF_1

3D RF Mesh Field

&MESH_RF_2

&END

3D RF Mesh Field

&MESH_RF_3

&END

3D RF Mesh Field

&MESH_RF_4

&END

3D RF Mesh Field

&MESH_RF_5

&END

3.0 Output files

3.1 File run_beam

x 1 in	y 2 out	3	4	5	6	7	8	9	10	11	12	13	14	15	16
z(cm)	T	x_envelope(cm)	y_envelope(cm)	bunch(deg)	energy(MeV)	Eff_accel	Eff_transp	px_emitt(cm*mrd	py_emitt(cm*mrd	dW/W	alpha_x	alpha_y	beta_x(cm)	beta_y(cm)	zpz_emitt
4.76071e-3	0.00000	0.89452	0.89258	107.57450	0.04692	1.00000	1.00000	8.87925e-11	8.95132e-11	2.58248e-4	7.43363e-3	-3.61855e-3	9.01036e+10	8.89907e+10	7.36859e-3
0.18475	0.01000	0.89489	0.89295	107.58420	0.04691	1.00000	1.00000	5.71829e-4	5.62901e-4	2.72208e-3	-32.67530	-33.05910	14004.96000	14165.44000	2.72451e-3
0.36474	0.02000	0.89564	0.89370	107.60370	0.04691	1.00000	1.00000	1.14351e-3	1.12605e-3	5.44278e-3	-32.69816	-33.07027	7015.09700	7093.01200	5.27859e-3
0.54473	0.03000	0.89677	0.89483	107.63300	0.04691	1.00000	1.00000	1.70063e-3	1.67092e-3	8.16030e-3	-33.00658	-33.45577	4728.87900	4792.07600	7.90571e-3
0.72473	0.04000	0.89827	0.89632	107.67220	0.04692	1.00000	1.00000	2.26184e-3	2.21441e-3	0.01087	-33.12335	-33.69319	3567.46400	3628.07300	0.01052
0.90472	0.05000	0.90015	0.89819	107.72090	0.04692	1.00000	1.00000	2.79999e-3	2.74618e-3	0.01358	-33.48915	-34.00275	2893.83200	2937.73400	0.01310
1.08471	0.06000	0.90240	0.90044	107.77950	0.04692	1.00000	1.00000	3.32333e-3	3.26590e-3	0.01628	-33.90942	-34.35985	2450.32700	2482.60500	0.01567
1.26469	0.07000	0.90501	0.90305	107.84750	0.04692	1.00000	1.00000	3.84739e-3	3.78830e-3	0.01898	-34.23127	-34.61687	2128.83500	2152.68400	0.01821
1.44469	0.08000	0.90800	0.90604	107.92520	0.04692	1.00000	1.00000	4.35134e-3	4.25641e-3	0.02166	-34.65705	-35.27877	1894.74500	1928.60900	0.02071
1.62468	0.09000	0.91136	0.90938	108.01260	0.04692	1.00000	1.00000	4.82963e-3	4.72985e-3	0.02433	-35.20386	-35.79337	1719.77800	1748.45100	0.02321
1.80467	0.10000	0.91508	0.91310	108.10960	0.04692	1.00000	1.00000	5.27223e-3	5.22111e-3	0.02699	-35.91707	-36.11437	1588.26700	1596.88200	0.02565
1.98466	0.11000	0.91918	0.91718	108.21630	0.04693	1.00000	1.00000	5.74404e-3	5.71614e-3	0.02964	-36.35774	-36.37949	1470.89000	1471.66700	0.02805

File contains output beam parameters

z — average longitudinal coordinate of the beam (cm)

T — dimensionless time (in RF scale)

x_envelope — $= 2\sqrt{< x^2 >}$ double rms beam size in x-direction (cm)

y_envelope — $= 2\sqrt{< y^2 >}$ double rms beam size in y-direction (cm)

bunch — $= \frac{4\sqrt{< z^2 >}}{\beta\lambda}$ four rms longitudinal beam size in scale of RF period (degrees)

energy — average energy of the beam (MeV/charge)

Eff_accel — transmission efficiency of accelerated particles (ratio of particle within RF period to total number of injected particles)

Eff_transp — transmission efficiency of transported particles (ratio of particle inside the channel to total number of injected particles). Eff_transp is a fraction of particles which are in the channel (both accelerated and non-accelerated).

xpx_emitt (π*cm*mrad) four rms normalized beam emittance $VX = \frac{4}{mc}\sqrt{< x^2 >< P_x^2 > - < xP_x >^2}$

ypy_emitt (π*cm*mrad) four rms normalized beam emittance $VY = \frac{4}{mc}\sqrt{< y^2 >< P_y^2 > - < yP_y >^2}$

BEAMPATH calculates xpx_emittance and ypy_emittance at every moment of time based on instantenious particle distributions. When head of the bunch is, for example, in a quadrupole, but the rest of the bunch is outside of quadrupole, emittances at (x-P_x), (y_P_y) planes are combinations of two different distributions. It dissapears when all particles are in the same element.

dW/W — $= 2\frac{\sqrt{< W^2 >}}{W}$ two rms energy spread

alpha_x — rms Twiss parameter of the beam, $\alpha_x = -4\frac{< xP_x >}{VX}$

alpha_y rms Twiss paramete of the beam, $\alpha_y = -4\dfrac{<yP_y>}{VY}$

beta_x(cm) rms Twiss parameter of the beam $\beta_x = 4 <x^2>/E_x$

beta_y(cm) rms Twiss parameter of the beam $\beta_y = 4 <y^2>/E_y$

zpz_emitt four rms normalized beam emittance in (z, P_z), π*cm*mrad $VZ = \dfrac{4}{mc}\sqrt{<z^2><p_z^2> - <zp_z>^2}$

3.2 Files 1001, 1002, 1003, …..

Files contain information about particle positions, momentum, and field at fixed moments of time. Files are generated after fixed interval in integration steps defined by parameter NOUT:

NOUT = 0 - no files

NOUT =1 - files are created at every time step

NOUT =2 – files are created at every next time step and so on.

i	x(cm)	y(cm)	z(cm)	r(cm)	px	py	pz	Ex(kV/cm)	Ey(kV/cm)	Ez(kV/cm)	Bx(Tesla)	By(Tesla)	Bz(TBz(Tesla)	Energy(MeV)	Sx	Sy	Sz	Polarization	Y/N
1.00000	0.20686	0.50082	448.31220	0.54186	4.20265e-5	-3.38254e-4	0.03999	5.69514e-3	0.01797	0.00000	0.00000	0.00000	0.00000	0.75082	0.00000	0.00000	0.00000	0.00000	1.00000
2.00000	-0.73432	0.60794	448.31220	0.95332	-3.01728e-4	-3.60462e-4	0.03999	-0.01503	0.01340	0.00000	0.00000	0.00000	0.00000	0.75087	0.00000	0.00000	0.00000	0.00000	1.00000
3.00000	0.17577	0.13839	448.31220	0.22371	6.20955e-5	-1.14545e-4	0.03999	6.03233e-3	4.44648e-3	0.00000	0.00000	0.00000	0.00000	0.75077	0.00000	0.00000	0.00000	0.00000	1.00000
4.00000	0.70835	0.33422	448.31220	0.78324	1.90897e-4	-2.38561e-4	0.03999	0.01836	9.07640e-3	0.00000	0.00000	0.00000	0.00000	0.75081	0.00000	0.00000	0.00000	0.00000	1.00000
5.00000	0.13042	0.94308	448.31220	0.95206	-1.00518e-5	-6.70770e-4	0.03999	2.19690e-3	0.02100	0.00000	0.00000	0.00000	0.00000	0.75098	0.00000	0.00000	0.00000	0.00000	1.00000
6.00000	0.74910	0.40731	448.31220	0.85267	2.76831e-4	-2.65583e-4	0.03999	0.01823	0.01072	0.00000	0.00000	0.00000	0.00000	0.75083	0.00000	0.00000	0.00000	0.00000	1.00000
7.00000	0.91603	-0.71399	448.31220	1.16142	3.26434e-4	4.26218e-4	0.03999	0.01452	-0.01139	0.00000	0.00000	0.00000	0.00000	0.75090	0.00000	0.00000	0.00000	0.00000	1.00000
8.00000	0.34753	0.40336	448.31220	0.53243	8.77618e-5	-2.78099e-4	0.03999	0.01070	0.01476	0.00000	0.00000	0.00000	0.00000	0.75081	0.00000	0.00000	0.00000	0.00000	1.00000
9.00000	0.21220	0.51370	448.31220	0.55581	1.37658e-4	-3.80532e-4	0.03999	5.70160e-3	0.01805	0.00000	0.00000	0.00000	0.00000	0.75084	0.00000	0.00000	0.00000	0.00000	1.00000
10.00000	-0.29365	0.11461	448.31220	0.31522	-1.70792e-4	-1.91124e-4	0.03999	-0.01067	2.94696e-3	0.00000	0.00000	0.00000	0.00000	0.75080	0.00000	0.00000	0.00000	0.00000	1.00000
11.00000	0.14245	0.84854	448.31220	0.86041	-1.91943e-5	-5.82344e-4	0.03999	2.66517e-3	0.02125	0.00000	0.00000	0.00000	0.00000	0.75092	0.00000	0.00000	0.00000	0.00000	1.00000

i particle number

x,y,z particle positions (cm)

p_x, p_y, p_z canonical particle momentum divided by *mc*

E_x, E_y, E_z electric field acting at particles (kV/cm)

B_x, B_y, B_z magnetic field acting at particles (Tesla)

Energy particle energy (MeV)

S_x, S_y, S_z components of particle spin vector

Polarization Polarization of particle (defined by the user in namelist $PARTIC)

Y/N =1 particle inside channel

=0 particle is lost at the aperture

3.3 Files 2001, 2002, 2003,…..

Files contain information about particle distribution at fixed points ZPLANE defined in namelist $OUTPUT

i	x(cm)	y(cm)	z(cm)	px	py	pz	T	x_prime	y_prime
1.00000	0.20686	0.50082	448.31230	4.20265e-5	-3.38254e-4	0.03999	16.33945	1.05093e-3	-8.45847e-3
2.00000	-0.73432	0.60794	448.31230	-3.01728e-4	-3.60462e-4	0.03999	16.33945	-7.54509e-3	-9.01381e-3
3.00000	0.17577	0.13839	448.31230	6.20955e-5	-1.14545e-4	0.03999	16.33945	1.55278e-3	-2.86434e-3
4.00000	0.70835	0.33422	448.31230	1.90897e-4	-2.38561e-4	0.03999	16.33945	4.77362e-3	-5.96553e-3
5.00000	0.13042	0.94308	448.31230	-1.00518e-5	-6.70770e-4	0.03999	16.33945	-2.51358e-4	-0.01677
6.00000	0.74910	0.40731	448.31230	2.76831e-4	-2.65583e-4	0.03999	16.33945	6.92250e-3	-6.64123e-3
7.00000	0.91603	-0.71399	448.31230	3.26434e-4	4.26218e-4	0.03999	16.33945	8.16288e-3	0.01066
8.00000	0.34753	0.40336	448.31230	8.77618e-5	-2.78099e-4	0.03999	16.33945	2.19459e-3	-6.95421e-3
9.00000	0.21220	0.51370	448.31230	1.37658e-4	-3.80532e-4	0.03999	16.33945	3.44230e-3	-9.51567e-3
10.00000	-0.29365	0.11461	448.31230	-1.70792e-4	-1.91124e-4	0.03999	16.33945	-4.27087e-3	-4.77931e-3

i	particle number
x,y,z	particle positions (cm)
p_x, p_y, p_z	canonical particle momentum divided by *mc*
T	time
x_prime	$= p_x / p_z$
y_prime	$= p_y / p_z$

*The program creates z-output (x,x',y,y',T,z) at points z=zplane generating files fort.2001, fort.2002, etc.. Points zplane have to be separated by minimum distance of beta*wavelength. To calculate beam emittance at z=zplane, files fort.2001, fort.2002,... have to be proceeded by the program available in folder PhaseSpaceDistributions_2000. Rename fort.2001 by 2 and run ./a.exe. Then, the output file "Beam Parameters" contains values of emittances, and beam sizes.*